

Electromagnetic field induced transitions in an exciton confined in three dimensional parabolic potential

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Abstract

It is shown that the energy spectrum of exciton strongly depends on the confining radius, strength of the parabolic potential and of course on the Coulomb interaction strength. The interaction of such confined excitons, with microwave field is studied, using non perturbative Floquet method. The Floquet method is quite reliable when dealing with microwave-matter interaction. The multiphoton excitation spectrum of excitons is probed with the variation of microwave frequencies, intensity and the confining parameters as well.

Key Words:- quantum dot, coupling matrix elements, electron-hole separation

1 Introduction

In the past decade, there has been considerable research in quantum dot systems due to their potential applications in optoelectronic devices and interesting fundamental physics. The quantum dot is a semiconductor nanocrystal. The energy spectrum of a quantum dot is different from that of a bulk semiconductor, in the sense the energy levels being discrete in a quantum dot (QD). This is because a particle (such as electron or a hole) in a quantum dot behaves as if it is confined to a three-dimensional potential well. The energy levels strongly depend on the quantum size [1-3], making the dot having unique properties useful in optoelectronic devices. Excitons are quite stable and have large lifetime [4] making them interesting from technological point of view. One of the important applications is their use in photovoltaic and solar cell devices [5]. The excitons confined in quantum heterostructures have large oscillator strengths and excitonic spectrum persists even at room temperature [6-8]. The binding energies, oscillator strengths and excitonic transitions increase with increasing confinement [9], giving an opportunity to design devices of choice.

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Due to their novel physical effects and potential device applications, lots of theoretical [10-27] and experimental works [28-31] have been devoted to the study of excitons in the quantum dots. Zhu et al. [10] and have calculated the binding energy of a hydrogenic donor impurity in a spherical quantum dot. Chuu et al. [11] have also reported the energies of hydrogenic impurity states with an impurity atom located at the center of a quantum dot and on the axis of a quantum-well wire.

The ground state properties of excitons in a quantum box have been studied using both the variational and configuration interaction method by Bryant [12]. Que [18] have reported the properties of the ground state of excitons in a quantum dot by solving the electron-hole effective mass Hamiltonian numerically, and two limiting cases: strong and weak confinement regimes analytically. Einevoll [20] have calculated single-hole energies in ZnS crystallites and bound-exciton energies in CdS and ZnS crystallites using a combined effective-bound orbital method and effective-mass approach. Kumar et al. [22] have calculated the self consistent numerical solutions in GaAs/AlGaAs heterostructures with confinement in all three spatial dimensions. Cakir et al. [23] have investigated the magnetic field effects on the binding energies of spherical quantum dot with finite confinement potential. Feddi et al. [24] have studied the Coulomb correlation, binding energy and inter-particle distance of a donor impurity placed in the well region of a spherical core/shell nanostructure, using the effective mass approximation. Lorke et al. [28] have used the far-infrared spectroscopy to show experimentally that coupling between quantum dots becomes visible in the electronic excitation spectrum. The binding energy of a negatively charged donor center D in a spherical quantum dot is studied as a function of barrier height and well radius, by use of variational approach [29].

Zielanski [32] has reported the changes in the local atomic arrangement in an alloyed self-assembled QD leading to a non-negligible in-plane optical activity of dark excitons along with triggering substantial fluctuations in bright excitons and dark excitons. The author found that the dark exciton optical spectra can vary significantly in the ensemble, from nanostructures having very small oscillator strength, to quantum dots with substantial fraction of bright exciton intensity. Safwan and Meshad [33] have presented the theoretical calculation of third-order nonlinear absorption coefficient and refractive index in a strongly three-dimensional exciton in a GaAs semiconductor QD. For an anisotropic QD, it has been found that the third order nonlinear absorption coefficient depends strongly on the quantum dot width. The linear and third-order nonlinear optical properties of an excitonic parabolic QD has

been studied by Gambhir and Prasad [34] in a static magnetic field. The eigenvalues, wavefunctions, dipole matrix elements and selection rules have been calculated analytically. Using effective mass approximation and compact density matrix approach, the nonlinear optical properties have been studied. Mommadi et al [35] have reported the exciton-phonon properties in cylindrical QD with parabolic confinement potential in the presence of electric field. To investigate the ground state binding energy of the exciton, the variational approach and the effective mass approximation has been used. It has been found that the electric field has an important impact on the excitonic properties in the QD considered. Gambhir et al [36] have analysed the electromagnetically-induced transparency in a parabolic QD with excitonic effects in a static magnetic field, a resonant probe field and a coupler field. The authors examined the complex electric susceptibility, absorption, dispersion group index and the combined effects of external factors such as magnetic field, hydrostatic pressure, temperature and dimensions. The excitonic states in canonical QDs under electric and magnetic field have been reported by Heyn et al [37] using the effective mass and parabolic band approximations and the finite element method. The authors have calculated the electron and hole positions along the axial axis, the overlap integral, the ground state lifetime for the uncorrelated pair and electron-hole Coulomb interaction as a function of applied electric and magnetic fields. The exciton absorption spectra in InGaAs prolate ellipsoidal QDs has been studied by Bao et al [38] showing the evidence of existence of the three level microwave optical Stark effect of excitons as the initial excitation absorption peak is split into two new peaks. This is the consequence of the splitting of the electron quantized levels due to the effect of the strong resonant pump microwave. The characteristics of the exciton absorption spectra has been investigated by calculating the transition rate of the interband transition using the renormalized wavefunction theory. The exciton absorption spectra depends strongly on the energy of the pump microwave and geometric shapes of the QDs.

The transfer of information at high speed is done by using light with optical fibres and electronic transistors are being used in the information processing in communication system. There is problem in the conversion between optical and electronic signals, which can be solved with the help of optical transistors. Research is being done to create optical transistors by using excitons and polaritons [39-41]. Charge transport can be facilitated by dephasing the excitons into uncorrelated electron-hole pair. In addition, the size dependent properties of excitons and multi-excitons [42] have been used in the

field of emissive displays, biological and biomedical fluorescence imaging [43]. To facilitate charge transport excitons may dephase into uncorrelated electron-hole pairs [44].

In this work, we have studied the exciton in a semiconductor parabolic QD and evaluated the energy of different excitonic states for different values of dielectric constants and confining potentials. In Section 2, we describe the theory of the exciton in a quantum dot and its interaction with the microwave field using Floquet theory. Section 3 deals with the Results and Discussion followed by conclusion.

2 Theory

In the effective mass approximation, the exciton in a quantum dot with semi-parabolic confinement, is described by the Hamiltonian[18] as:

$$H = -\frac{\hbar^2}{2m_e^*}\nabla_e^2 - \frac{\hbar^2}{2m_h^*}\nabla_h^2 - \frac{\epsilon^2}{\epsilon|\vec{r}_e - \vec{r}_h|} + V_c^e(\vec{r}_e) + V_c^h(\vec{r}_h) \quad (1)$$

where $m_{e,h}^*$ and $\vec{r}_{e,h}$ are the effective masses and positions of the electron and hole, e is the elementary charge and ϵ is the dielectric constant of the material.

The semi-parabolic confining potential, $V_c^i(\vec{r}_i)$, is defined as:

$$V_c^i(\vec{r}_i) = \begin{cases} \frac{1}{2}m_i^*\omega_c^2 r_i^2 & \text{for } r_i \geq 0 \end{cases} \quad (2)$$

where ($i = e, h$) and $\hbar\omega_c$ is the strength of the confining potential.

Introducing the centre-of-mass coordinate, $\vec{R}$, and the relative coordinates, $\vec{r}$, as:

$$\vec{R} = \frac{m_e^*\vec{r}_e + m_h^*\vec{r}_h}{m_e^* + m_h^*}, \quad (3)$$

and

$$\vec{r} = \vec{r}_e - \vec{r}_h, \quad (4)$$

The Hamiltonian in Equation (1) can be written as:

$$H = H_{COM} + H_{rel}, \quad (5)$$

$$H_{COM} = -\frac{\hbar^2}{2M} \nabla_R^2 + \frac{1}{2M} \omega_c^2 R^2 \quad (6)$$

and

$$H_{rel} = -\frac{\hbar^2}{2\mu} \nabla_r^2 + \frac{1}{2\mu} \omega_c^2 r^2 - \frac{\epsilon^2}{\epsilon |\vec{r}|} \quad (7)$$

where $M=m_e^*+m_h^*$ is the total mass and $\mu = \frac{m_e^* m_h^*}{m_e^* + m_h^*}$ is the reduced mass.

Thus , the total wavefunction of the system is defined as:

$$\psi(\vec{r}_e, \vec{r}_h) = \Phi(R) \phi(r). \quad (8)$$

The total energy of the system is

$$E = E_R + E_r \quad (9)$$

The wavefunctions and eigenenergies of the COM motion is given by:

$$\Phi(R) = N_l \exp\left(-\frac{a^2 R^2}{2}\right) H_{2l+1}(\alpha R), \quad (10)$$

and

$$E_R = \left(2l + \frac{3}{2}\right) \hbar \omega_c \quad (11)$$

where $\alpha = \sqrt{\frac{M \omega_c}{\hbar}}$ and

$$N_l = \left[\frac{\sqrt{\pi} 2^{2l} (2l+1)!}{\alpha} \right]^{-1/2}, \quad (12)$$

where H_{2l+1} are the Hermite polynomial of order $2l+1$.

The relative motion wavefunction and eigenenergies are given by the Schrodinger equation:

$$\left[-\frac{\hbar^2}{2\mu} \nabla_r^2 + \frac{1}{2\mu} \omega_c^2 r^2 - \frac{\epsilon^2}{\epsilon |\vec{r}|} \right] \phi(r) = E_r \phi(r) \quad (13)$$

Since the second and third term on the left hand side of Equation (13) depends on $|\vec{r}|$ only, the angular part of the Hamiltonian is solved trivially. Equation (13) gives one-dimensional differential equation, which we have solved numerically using nine-point finite difference method.

The size of the quantum dot is defined as:

$$R_0 = \sqrt{\frac{\hbar}{\mu \omega_c}} \quad (14)$$

The electron-hole separation r_s in the exciton ground state is defined as:

$$r_s^2 = \langle r^2 \rangle, \quad (15)$$

where the angular brackets represent the expectation value of the ground state.

Further, we have studied the interaction of our system with the periodic field in the form of a monochromatic microwave field, $E(t) = E_e \cos(\omega_e t)$, using Floquet quasienergy formalism. The quasi-energy-state can be determined through the solution of a stationary matrix eigenproblem. This method was first introduced by Shirley [44] for a two level quantum system in a periodic field, which has proved to be quite useful in understanding the evolution of bound state with the periodic microwave field. Let us consider the interaction of our system with the monochromatic linearly polarized periodic microwave field along the z-axis and dipole moments are taken to be aligned with the polarisation direction.

The time dependent Schrodinger equation for the microwave field interaction can be written as:

$$i \frac{\partial \Psi_p}{\partial t} = [H_{rel} - E_e r \cos(\omega_e t)] \Psi_p \quad (16)$$

where $H_{rel}(\vec{r})$ is given by Equation (7), E_e is the strength and ω_e is the frequency of the microwave field.

According to Floquet theorem, the wavefunction, $\Psi_p(\vec{r}, t)$, called the quasienergy-state can be written in the following form:

$$\Psi_p(\vec{r}, t)\phi(\vec{r}, t) = e^{-i\varepsilon_f t}\phi_p(\vec{r}, t) \quad (17)$$

where $\phi_p(\vec{r}, t)$ is called the Floquet wave function periodic in time and ε_f is the Floquet characteristic exponent or the quasienergy. Expanding $\phi_p(\vec{r}, t)$ and $H(t) = [H_{rel} - E_e \cos(\omega_e t)]$ in terms of Floquet state basis yields:

$$\phi_p(\vec{r}, t) = e^{-i\varepsilon_p t} \sum_{n=-\infty}^{\infty} C_p^{(n)}(r) e^{-in\omega_e t} \quad (18)$$

A quasienergy state can be considered as a superposition of stationary states with energies equal to $\varepsilon_p + n\omega_e$. The function $C_p^{(n)}$ can be further expanded in terms of an orthonormal set of unperturbed eigenfunctions so that

$$C_p^{(n)}(r) = \sum_q \phi_{pq}(r) e^{-in\omega_e t} \quad (19)$$

Substituting Eq. (18) and (19) in Eq. (16), we get the following set of coupled equations:

$$\sum_n \sum_q [p|\langle H^{(m-n)}|q\rangle - (\varepsilon_p + m\omega_e)\delta_{mn}\delta_{pq}]\phi_{pq}^{(n)} = 0 \quad (20)$$

The above set coupled equations can be recalibrated into an eigenvalue matrix equation:

$$\sum_s \sum_{s'} [pn|\langle H_F|ss'\rangle]\phi_{sq}^{(s')} = \varepsilon_q \phi_{pq}^{(n)} \quad (21)$$

where H_F is called the time-independent Floquet Hamiltonian. The matrix elements are given by:

$$\langle pn|H_F|qm\rangle = H_p^{(n-m)}q + m\omega_e\delta_{pq}\delta_{nm}. \quad (22)$$

The quasienergies are eigenvalues of the secular equation $|H_F - \varepsilon I| = 0$. The Floquet Hamiltonian acquires a block tridiagonal form. The quasienergies ε_{pn} and quasienergy state $|\varepsilon_{pn}\rangle$ can be determined by the solution of time-independent Floquet matrix eigenproblem. H_F has a periodic structure with only the number of $\omega_e s$ in the diagonal elements varying from one photon block to the other blocks. This structure owns the quasienergy eigenvalues and eigenvectors of Floquet Hamiltonian with the pe-

periodic properties. The probability of the occurrence of a transition between two quantum states, which is important for understanding many aspects of microwave behaviour, is given by:

$$P_{p \rightarrow q(t-t_0)} = |U_{qp}(t, t_0)|^2 = \sum_s \sum_m \langle qs | e^{-iH_F(t-t_0)} | p0 \rangle \langle pm | e^{-iH_F(t-t_0)} | qs \rangle \quad (23)$$

where $U_{qp}(t, t_0)$ is the time evolution operator that gives the amplitude that a system initially in the Floquet state $|p0\rangle$ at time t_0 evolve to the Floquet state $|qn\rangle$ by time t according to the time independent Floquet Hamiltonian H_F summed over n with weight factors $\exp(in\omega_e t)$. The quantity of experimental interest, however, is the transition probability averaged over initial times t_0 keeping the elapsed time $(t - t_0)$ fixed. This gives:

$$P_{p \rightarrow q(t-t_0)} = \sum_s |\langle qs | e^{-iH_F(t-t_0)} | p0 \rangle|^2 \quad (24)$$

Finally, averaging over $(t - t_0)$, one obtains the long-time average transition probability:

$$P_{p \rightarrow q(t-t_0)} = \sum_s \sum_{\nu\nu'} |\langle qs | \varepsilon_{\nu\nu'} \rangle \langle \varepsilon_{\nu\nu'} | p0 \rangle|^2 \quad (25)$$

The advantage of this method is that the rapidly varying optical frequency are removed from the time-dependent interaction Hamiltonian by transforming it into the time-independent Floquet Hamiltonian which can be diagonalized. We get the eigenvectors which are the dressed states or the adiabatic Floquet states of our quantum system and the eigenvalues are the eigenenergies.

3 Results and Discussion

In this work, we have studied the excitation of excitons in microwave field. The microwave field is continuous wave field. In order to apply Floquet theory to such a system one needs to evaluate the relevant parameters of the excitons confined in spherical plus semi parabolic potentials. We evaluated these by solving the time independent Schrodinger equation in relative motion (Equation 13) numerically using 9-point finite difference method. We obtained, well converged results for the energy eigenvalues.

In our numerical computations, the various parameters taken are: electron effective mass, $m_e^* = 0.067m_e$,

hole effective mass $m_h^*=0.099m_e$. We have computed the energy by taking three different values of dielectric constant, ϵ , =2.5, 5.0 and 12.8 and four different values of confining potential, $\hbar\omega_c=2.5, 5.0, 15.0$ and 54.4 meV .

In Table 1, are given the computed values of energies of the first fifteen states of the exciton with dielectric constant=2.5 and $R_0=1000 \text{ a.u.}$, for four different values of the confining potential, $\hbar\omega_c=2.5, 5.0, 15.0$ and 54.4 meV . The ground state energy i.e. $1s$ is negative for all the values of confining potential, while the energy of $1p$ state ($n=0, l=1$) is negative for $\hbar\omega_c=2.5, 5.0$ and 15.0 meV but is positive for $\hbar\omega_c=54.4 \text{ meV}$. The value of energy for any particular state keeps on increasing as the value of confining potential is increased. The energy of $2s$ state ($n=2, l=1$) is negative for $\hbar\omega_c=2.5, 5.0$ and 15.0 meV but is positive for $\hbar\omega_c=54.4 \text{ meV}$. The energy of $3s$ state ($n=3, l=1$) is negative only for $\hbar\omega_c=2.5$ and is positive for all the other values of $\hbar\omega_c$. The exciton energy also increases with increase in the value of l for a given value of n .

Table II and III are same as Table I but for dielectric constant 5 and 12.8 respectively. For $\epsilon=5$, the ground state energy is negative for $\hbar\omega_c=2.5, 5.0$ and 15.0 meV but is positive for $\hbar\omega_c=54.4 \text{ meV}$, while for $\epsilon=12.8$, the ground state energy is negative for $\hbar\omega_c=2.5, 5.0 \text{ meV}$ but is positive for $\hbar\omega_c=15.0$ and 54.4 meV . The energy of a given state increases as the values of ϵ is increased from 2.5 to 12.8. The changes in energy corresponds to nl values, is due to the fact that ϵ controls the value of effective Coulomb term in the relative Hamiltonian. With increase in ϵ , Coulomb interaction strength decreases, hence the energy of individual state increases.

In Table IV, are tabulated the energies of the exciton without Coulombic interaction. Now the ground state energy is not negative for any value of $\hbar\omega_c$. The trend of energies is same as for Tables I, II and III: increasing as the value of $\hbar\omega_c$ is increased and also increasing as the value of l is increased for a given n .

In Fig. 1 we have plotted the variation of energy of the exciton with the size of the quantum dot ($R_0=5-50 \text{ nm}$) for the first fifteen states. Here dielectric constant is taken to be 12.8 and confining potential as 5 meV . In panel (a), the energies are plotted for $n=0$ and $l=1-5$, i.e. $1s, 1p, 1d, 1f, 1g$; while the energies plotted in panels (b) and (c) correspond to $n=1, l=1-5$ and $n=2, l=1-5$, respectively. It is clear from each panel, that the energy of the exciton increases as we go from $ns \rightarrow np \rightarrow nd \rightarrow nf \rightarrow ng$. The value of excitonic energy is maximum at $R_0=5 \text{ nm}$ and decreases sharply at low values of R_0 , and then

gradually attaining a constant value at $R_0 > 30 \text{ nm}$.

In Fig. 2 is plotted the variation of ratio of electron-hole separation to R_0 with coupling frequency in the absence of microwave field. In a three-dimensional parabolic quantum dot, the spatial extent of an exciton is governed by the interplay between harmonic confinement and the Coulomb attraction between the electron and hole. At low values of ω_c , the confinement is weak and the Coulomb interaction dominates, allowing the electron and hole to remain spatially extended. Consequently, the exciton size increases, resulting in increase in the ratio of the electron-hole pair size to the dot size. As ω_c increases, the parabolic potential strengthens and progressively localizes both carriers toward the dot center, reducing the average electron-hole separation. This leads to a monotonic increase in the size ratio, which approaches $\simeq 0.68$ in the strong-confinement regime, indicating a crossover from Coulomb-dominated to confinement-dominated excitonic behavior.

Now, with the introduction of electromagnetic field, the energy spectrum gets modified, i.e. it gets dressed. The microwave-matter interaction dynamics depends on the energy level structure of the system under consideration and also on the interaction matrix elements. As the confinement and dot parameters change, the changes occur, which are quite evident from Tables I-IV. As mentioned, we have applied the Floquet theory [38] for the evaluation of the dressed states of the excitons. It is well known, the advantage of Floquet theory is that along with rotating wave approximation (RWA), the time dependent Schrodinger equation is finally reduced to a time independent Floquet matrix. To get the dressed states of the system, one has to truncate this infinite Floquet matrix to a finite one. We have taken enough number of photon blocks to get converged results.

In Fig. 3 is shown the variation of ratio of electron-hole separation to R_0 with the coupling frequency with microwave field at microwave frequency $= E_{1p} - E_{1s}$. When an external microwave field is applied that is resonant with the interlevel transition energy, $\hbar\omega_e = E_{1p} - E_{1s}$, the ratio of the exciton size to the quantum-dots size exhibits an enhanced dependence on the confinement frequency due to microwave-induced state mixing. At low confinement strengths, the resonant microwave efficiently couples the ground and excited excitonic states, increasing the delocalization of the relative electron-hole motion and yielding a larger size ratio. With increasing ω_c , the larger energy spacing between confined levels suppresses microwave-assisted delocalization, resulting in progressive localization of the exciton. In the strong-confinement regime, the harmonic potential dominates over both Coulomb interaction and

microwave coupling, forcing the exciton to remain tightly confined within the dot and resulting in a large constant exciton size to QD size ratio.

In Fig. 4 is shown the variation of the ratio of electron-hole separation to R_0 with the microwave frequency for three different values of microwave intensities, $I = 3.5 \times 10^8, 3.5 \times 10^6$ and 3.5×10^4 W/cm^2 at the coupling strength = 2 meV. The figure shows the effect of the microwave intensity on exciton localization. At low microwave intensity, the interaction between the exciton and the radiation field is weak, and the exciton size is primarily determined by the balance between Coulomb attraction and harmonic confinement, leading to a relatively large size ratio. As the microwave intensity increases, enhanced microwave-matter coupling induces stronger mixing between excitonic states and leads to the formation of microwave-dressed wave functions. This results in increased localization of the electron-hole pair and a systematic reduction in the exciton-to-dot size ratio. At the highest microwave intensity, the suppression of excitonic delocalization is most pronounced, demonstrating that microwave fields provide an effective means to control exciton spatial confinement.

The introduction of the microwave field induces the mixing of levels. The mixing of levels depends on the field parameters. As shown in Fig. 5, where the variation of the dressed exciton energy of first fifteen states is shown with the microwave energy for different values of the intensity of microwave field. The dielectric constant used is 12.8 and confining strength is 54.4 meV. In panel (a) the intensity of the microwave field $I = 3.5 \times 10^8$ and for panel (b), the intensity is $I = 3.5 \times 10^6$ W/cm^2 . The exciton energy decreases with increase in microwave energy. The dressed state undergo avoided crossings with the frequency. At lower field strength (panel (b)) the dressed states, undergo multiple avoided crossings, with the frequency, where multiphoton transitions are supposed to take place. The inset in (panel (b)), shows the behaviour of energy levels in low microwave energy range (from 0-50 meV). If the intensity is increased (panel (a)), the crossings become more evident.

The variation of probability of various states with the microwave energy for intensity $I = 3.5 \times 10^8$ W/cm^2 (panel (a)), $I = 3.5 \times 10^6$ W/cm^2 (panel (b)) and $I = 3.5 \times 10^4$ W/cm^2 (inset of panel (b)) is presented in Fig. 6. Here, $\epsilon=12.8$ and $\hbar\omega_c=54.4$ meV. As is clear from the figure, at high microwave intensity, strong resonant coupling leads to efficient population transfer from the ground excitonic state to excited states, manifested by sharp probability peaks and rapid variations characteristic of strong Rabi-type mixing. These features indicate the formation of microwave-dressed excitonic states with

dynamically shared populations. At lower microwave intensity, the ground state remains predominantly occupied over a wide range of microwave energies, and only weak, broad probability peaks appear near resonance, indicating suppressed state mixing and reduced transition rates.

Finally, in Fig. 7 is shown the variation of the occupation probability of various excitonic states as a function of the microwave energy for two different confinement strengths: $\hbar\omega_c = 2$ meV (panel (a)) and $\hbar\omega_c = 54.4$ meV (panel (b)). The calculations are performed for $\varepsilon = 12.8$ and a microwave intensity $I = 3.5 \times 10^6$ W/cm². The figure clearly illustrates the influence of confinement strength on microwave-induced population redistribution. In the weak-confinement regime ($\hbar\omega_c = 2$ meV), the reduced energy spacing between excitonic levels enables efficient resonant coupling with the microwave field, leading to strong redistribution of state probabilities and pronounced microwave-induced mixing. In contrast, under strong confinement ($\hbar\omega_c = 54.4$ meV), the excitonic states become more localized and well separated in energy, which strongly suppresses microwave-induced transitions. As a result, the ground excitonic state remains predominantly populated, while the excited-state probabilities are significantly reduced and display only weak resonant features. This comparison highlights the crucial role of confinement strength in stabilizing excitonic states and limiting microwave-driven population control in quantum dots.

4 Conclusion

The excitonic states of a spherical quantum dot with semi-parabolic potential have been calculated numerically. The energy levels of the excitons and the matrix elements depend on the relative Coulomb strength, confining potential, strongly. The response of excitons to microwave field shows absorption spectra, that depicts multiphoton structure.

In conclusion we have studied the excitonic response to the interaction with continuous electromagnetic field, of moderate intensity using non perturbative quasi energy method. The method used here has been extensively applied in the field of atomic and molecular physics to study the light-matter interaction.

Firstly the energy spectra of confined excitons, under spherical and semiparabolic confinements is evaluated by numerically solving the time independent Schrodinger equation. The energy spectrum shows hydrogen like behavior in case of strong Coulomb interaction and then non-hydrogenic behavior

in case of strong confinements.

The multiphoton excitation spectrum of excitons is very important in the devices those are ultrasensitive to the frequency of the electromagnetic radiations. These devices are of practical use for biomedical imaging [39] and references therein, and for other applications, where excitons being charge carriers such as excitonic transitions [40].

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Table I: Energy of different states of exciton for different values of $\hbar\omega_c$ and $\epsilon=2.5$.

n	l	2.5 meV	5.0 meV	15.0 meV	54.4 meV
0	0	-86.93085326	-86.77006815	-85.11252055	-67.25175257
0	1	-21.21399135	-19.80764850	-9.224590872	55.60933523
0	2	-7.212018206	-3.661158656	18.63392138	128.9701368
0	3	1.142850444	6.273024533	39.52444398	193.0753499
0	4	8.846791700	15.01158281	58.08245456	253.6347745
1	0	-20.99062613	-19.02495229	-4.008361512	89.24136074
1	1	-5.449771223	-0.957758376	29.07066271	175.2038888
1	2	6.430556489	11.57680705	52.01891698	242.9727058
1	3	17.77070743	23.17668710	71.47545820	305.0953042
1	4	29.13826897	34.83589102	89.42645695	364.6848213
2	0	-4.270707576	0.703081552	36.04026386	212.9624894
2	1	11.60705837	16.86072889	63.17928886	290.3264102
2	2	27.12588785	32.24439211	84.29584120	355.4409339
2	3	42.03132700	47.21703958	103.1270890	416.374303
2	4	56.99385860	62.33931665	121.0788280	475.3090592

Table II: Same as Table I but for $\epsilon=5.0$.

n	l	2.5 meV	5.0 meV	15.0 meV	54.4 meV
0	0	-21.53359718	-20.93317412	-15.9343027	18.54813943
0	1	-3.409882113	-0.518031694	16.49702456	97.73999745
0	2	3.730940244	8.366065851	36.41064431	160.4364093
0	3	10.24907631	16.01087823	53.94021479	219.3340789
0	4	17.14516023	23.70052443	70.55066214	276.6620076
1	0	-2.221332603	1.680412909	26.04111285	142.0478805
1	1	8.513709495	13.40546914	49.27641979	210.9558842
1	2	18.45752987	23.62206184	67.76509412	271.5624909

1	3	28.46648312	33.93353289	84.79716566	329.6302464
1	4	38.98711969	44.76594348	101.2055397	386.5292068
2	0	12.47807360	17.66006377	59.90394690	257.1190754
2	1	27.04494771	32.02115716	80.93834855	322.5573986
2	2	40.46759862	45.48649566	98.82297644	382.0570914
2	3	53.97199354	59.14648572	115.7848041	439.6019191
2	4	68.00406573	73.37167264	132.5538493	496.2033129

Table III: Same as Table I but for $\epsilon=12.8$.

n	l	2.5 meV	5.0 meV	15.0 meV	54.4 meV
0	0	-2.14165437	-0.295521011	10.05433446	59.04888340
0	1	4.274576909	8.162664896	29.74470068	121.4633989
0	2	9.668354831	14.84310437	46.39138803	178.8626290
0	3	15.52946024	21.61010525	62.29699456	234.9426378
0	4	22.07080952	28.83155520	77.8917104	290.4524979
1	0	8.117794142	12.69602236	42.71447714	172.1252493
1	1	16.82127945	21.70626451	60.60771224	231.7990462
1	2	25.50042413	30.69856340	76.86139321	288.5135667
1	3	34.80359475	40.32454458	92.62469971	344.3022361
1	4	44.87605134	50.71055641	108.1982090	399.6564588
2	0	24.17339129	29.04894297	73.94139238	283.0765190
2	1	36.29250522	41.14724169	91.20406074	341.6156010
2	2	48.37585635	53.36951610	107.3549904	397.9448357
2	3	61.09811412	66.28077677	123.3099215	453.5447334
2	4	74.61290735	80.00045479	139.4332500	508.7892850

Table IV: Energy of different states of exciton for different values of $\hbar\omega_c$ without Coulombic interaction.

n	l	2.5 meV	5.0 meV	15.0 meV	54.4 meV
0	0	4.59112096	7.612497730	22.50000088	81.60000000
0	1	8.543447948	12.97182756	37.50001228	136.00000000
0	2	13.28596674	18.75730902	52.50010220	190.40000000
0	3	18.83274175	25.09534283	67.50060500	244.80000000
0	4	25.18475975	32.06607142	82.50277192	299.20000000
1	0	14.93082441	19.47798162	52.50021982	190.40000000
1	1	21.92437187	26.82087195	67.50163456	244.80000000
1	2	29.89406310	35.12720805	82.50857052	299.20000000
1	3	38.79776734	44.35822634	97.53443525	353.60000000
1	4	48.60898253	54.48080255	112.6113838	408.00000000
2	0	31.76144180	36.44448777	82.51275493	299.20000000
2	1	42.05567118	46.86495118	97.55847772	353.60000000
2	2	53.34759546	58.33712461	112.7031711	408.00000000
2	3	65.60667340	70.79935305	128.0638016	462.40000000
2	4	78.81044551	84.21282957	143.8011393	516.80000000

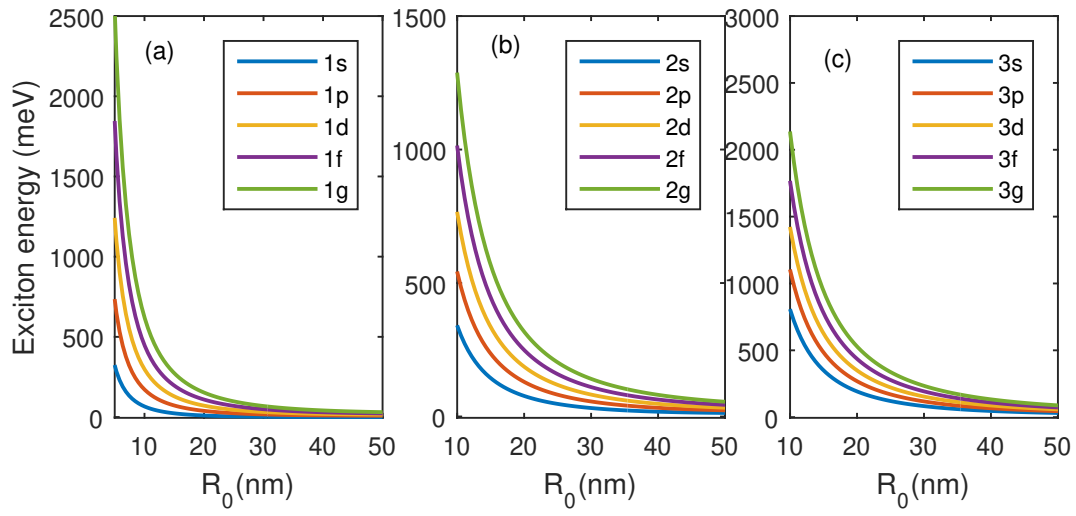


FIG. 1: Variation of energy of various excitonic states with QD size.

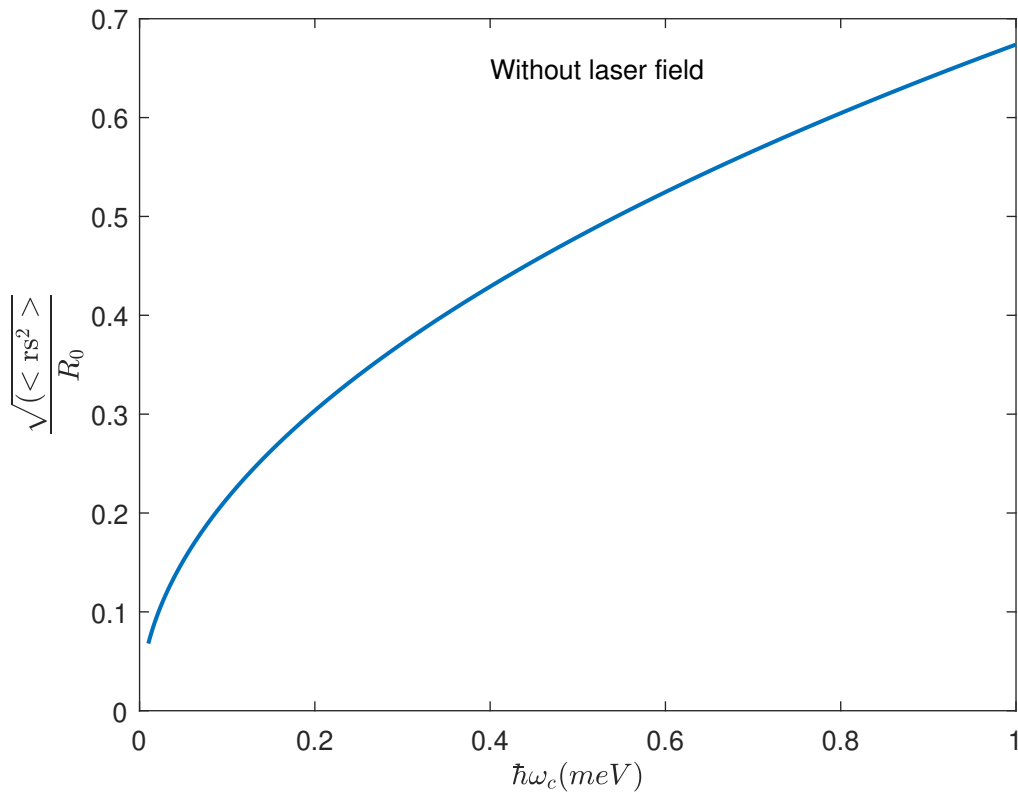


FIG. 2: Variation of ratio of electron-hole separation to R_0 with the coupling strength without microwave field.

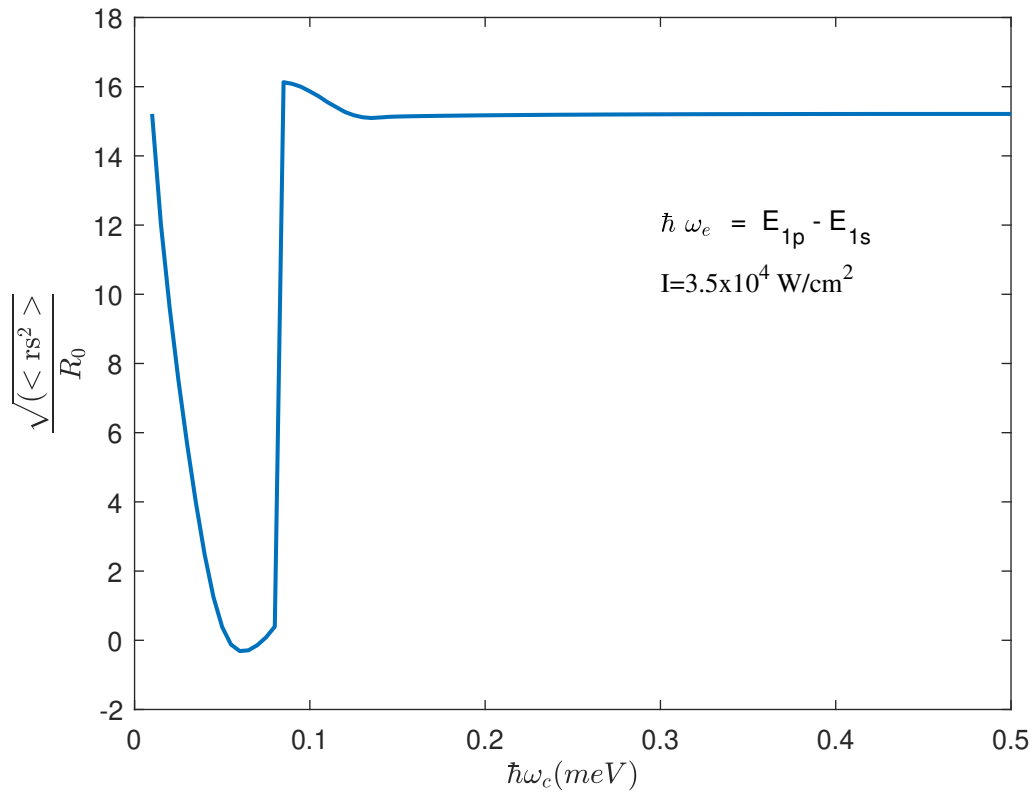


FIG. 3: Variation of ratio of electron-hole separation to R_0 with the coupling strength in the presence of microwave field. The microwave energy = $E_{1p} - E_{1s}$.

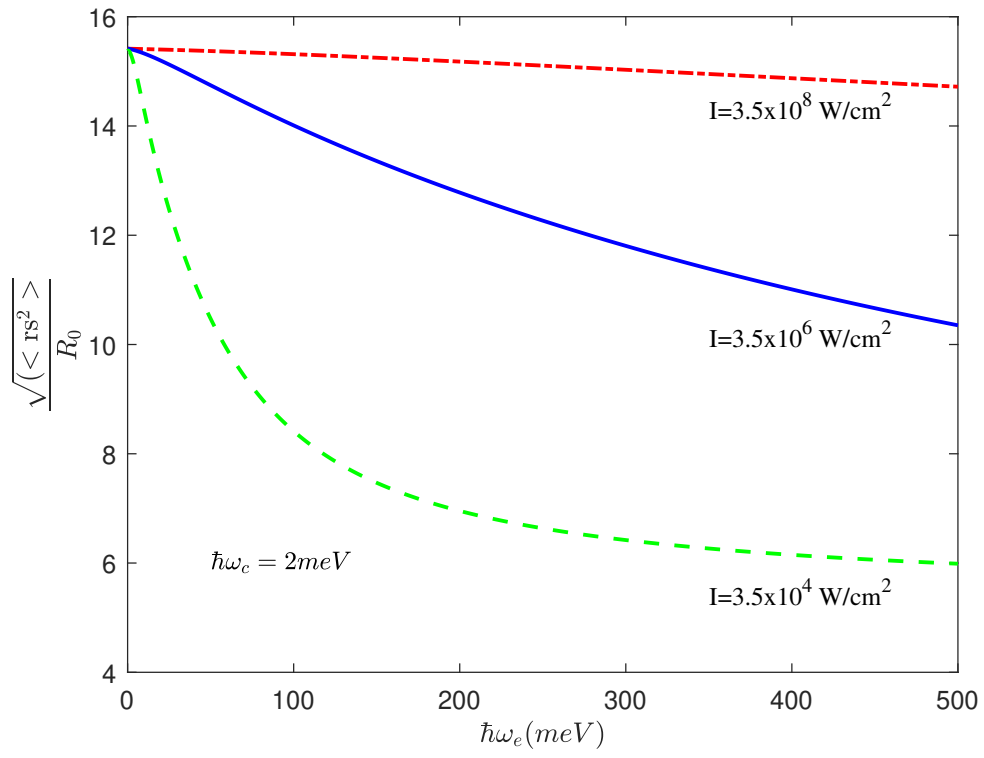


FIG. 4: Variation of ratio of electron-hole separation to R_0 with the microwave field energy. The coupling energy = 2 meV.

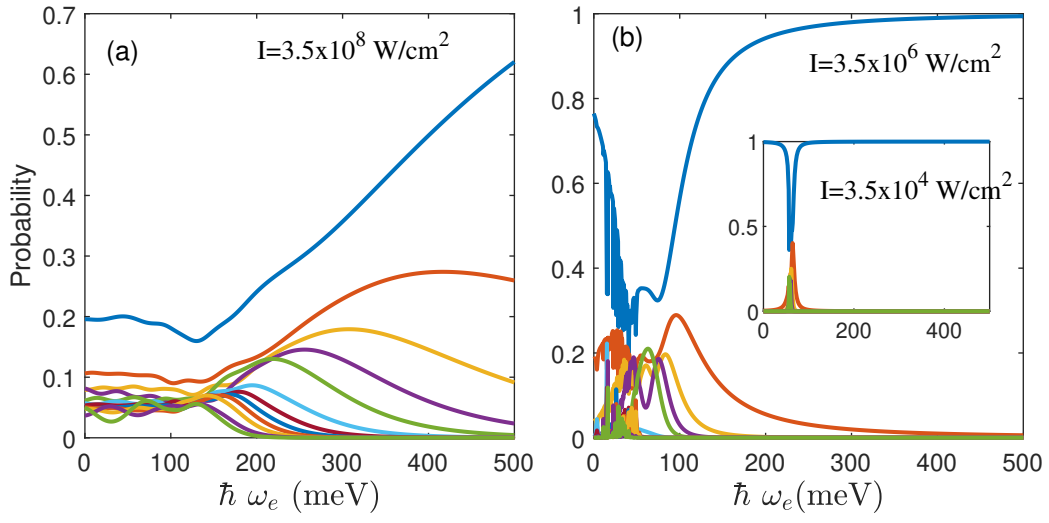


FIG. 5: Variation of energy of various excitonic states in a quantum dot with the microwave energy.

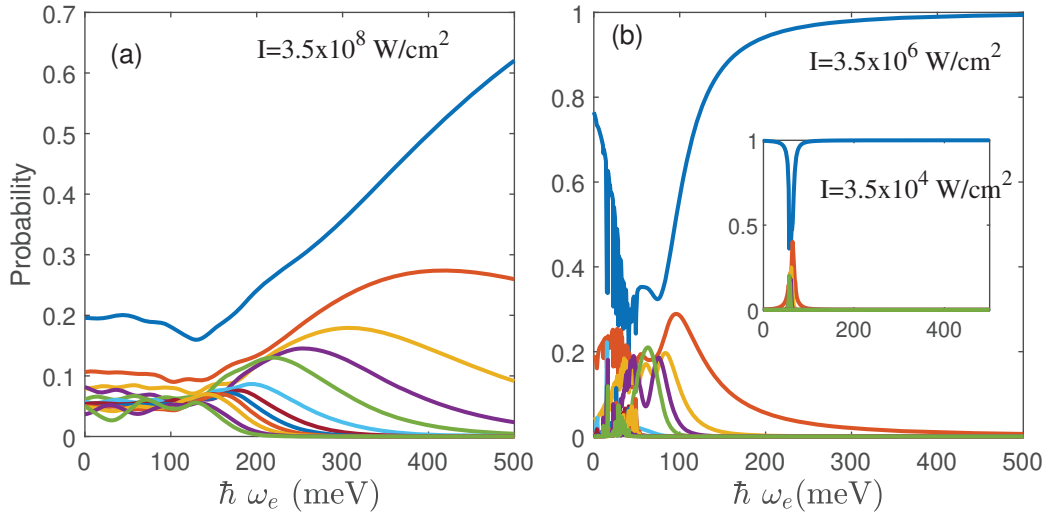


FIG. 6: Variation of probability of various excitonic states in a quantum dot with microwave energy. The intensity of the field is $3.5 \times 10^8 \text{ W/cm}^2$ (panel (a)), $3.5 \times 10^6 \text{ W/cm}^2$ (panel (b)) and $3.5 \times 10^4 \text{ W/cm}^2$ (inset panel (b))

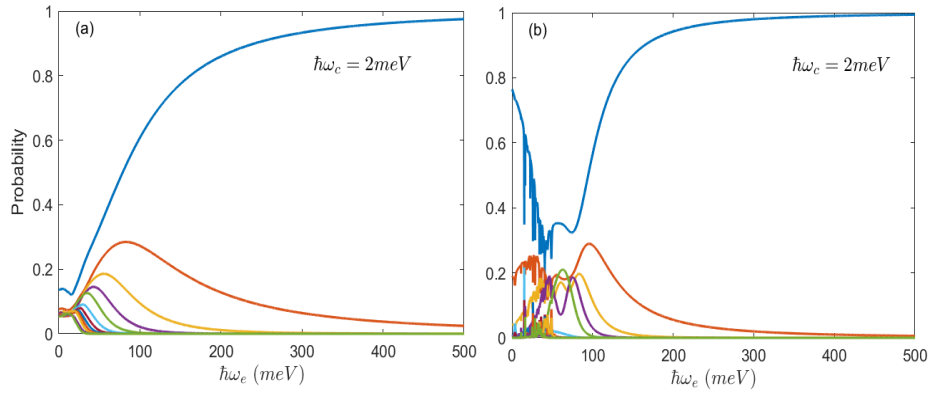


FIG. 7: Variation of probability of various excitonic states in a quantum dot with the microwave energy for two values of confining strength, 2 meV (panel (a)) and 54.4 meV (panel (b)). The intensity taken is $3.5 \times 10^6 \text{ W/cm}^2$